GE
Transportation

Aftertreatment

Impact to locomotives & locomotive operations

California Air Resources Board
Sacramento, CA
June 6th, 2007

Discussion topics

- → Where we are & where are we going
- → Tier 4 PM
- → Tier 4 NOx
- → Space & other constraints
- → Operational impact
- → Development requirements
- → Summary

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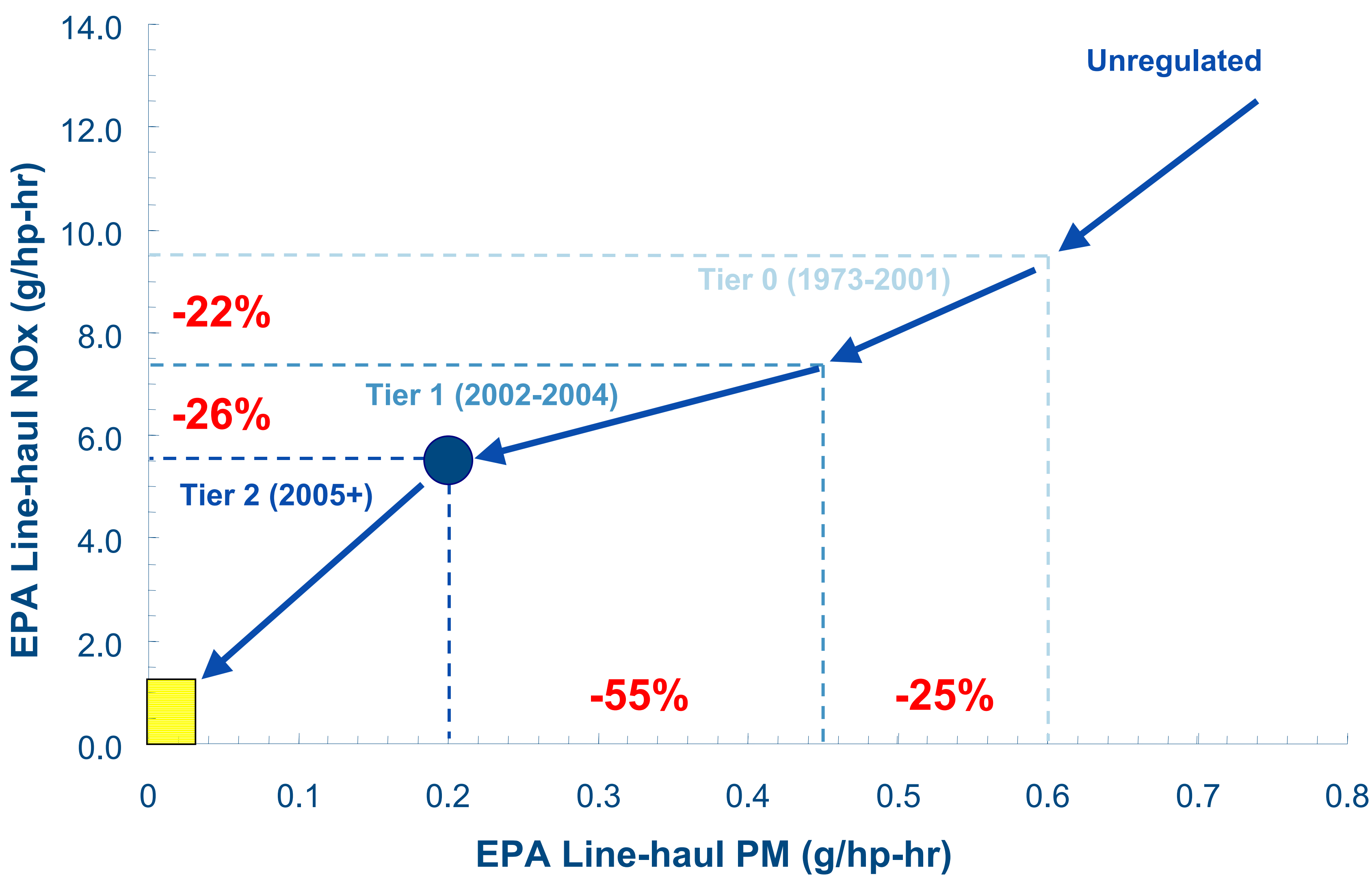
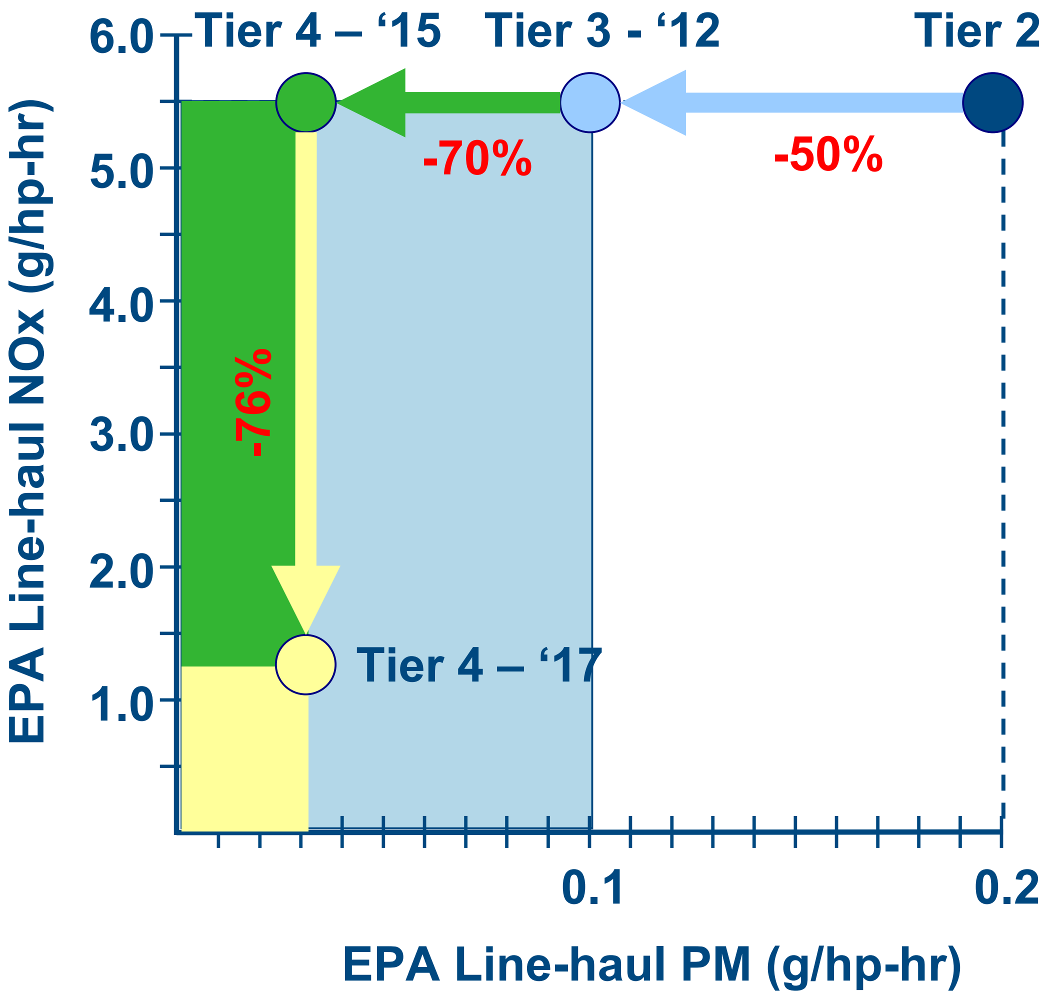
Where we have come from



Where we are going



Tier	Technology
3	- On-engine technologies - Ultra low sulfur diesel
4	- All Tier 3 technology - Diesel particulate filter (DPF) - Ultra low sulfur diesel
4	- All Tier 4 PM technology - NOx aftertreatment (Urea SCR) - Ultra low sulfur diesel

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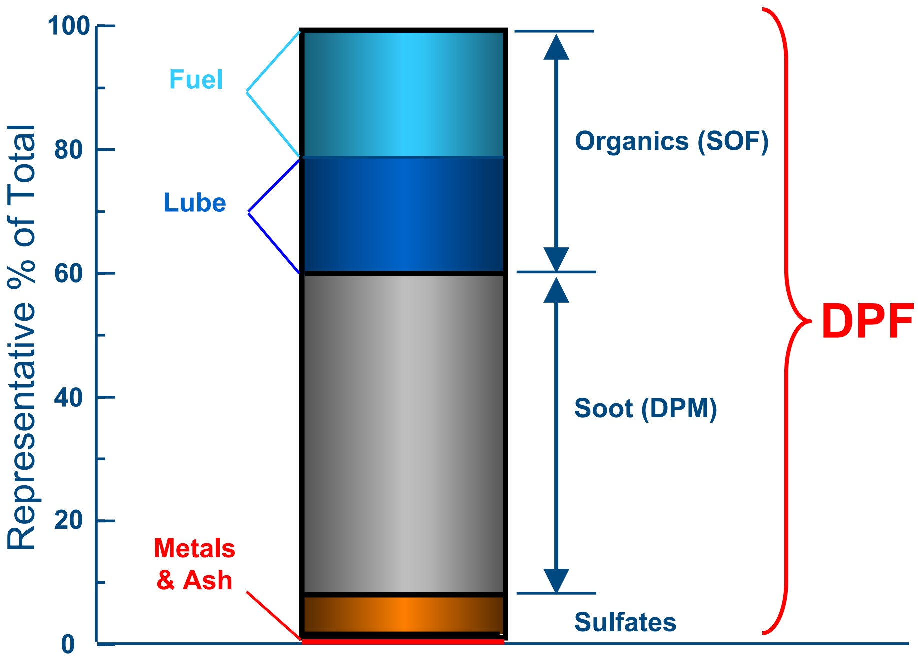
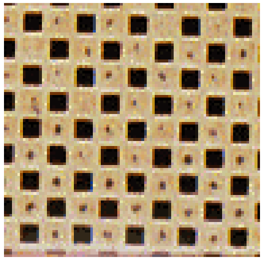
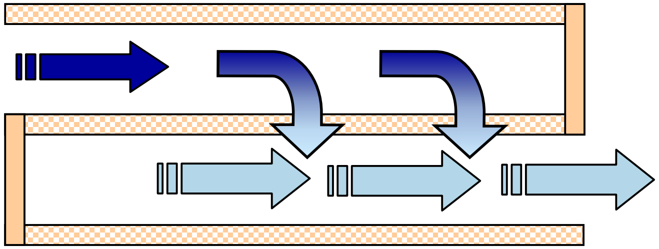
imagination at work

Diesel Particulate Filter

- Captures all forms of particulate matter
- 90+% PM reductions are achievable
- Captured material must be periodically
  burned off (regenerated)
  - Avoid high back pressure
  - SFC penalty
- Technology path defined
- Significant engineering challenge
- Logistics/handling challenges:
  - Size/weight/handling equipment
  - May require crane for change out







PM Aftertreatment Concerns

Consumables:

- 1 to 2 % SFC increase . . . 35 – 70 tons/year of CO_2
  - added backpressure
  - regeneration energy

Maintenance:

- Ash cleaning every 180 days a must to match service intervals
  - Similar to power cylinder replacement (will require crane)
  - UX exchange process
  - Waste handling & disposal

Durability:

- Anticipate replacement of DPF at end of useful life (engine overhaul)

Logistics:

- DPF maintenance, handling & exchange process
- Waste disposal

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Tier 4 NOx: Areas of Concern

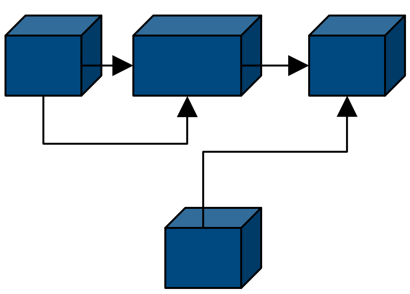
- No account for **carbon**, **ammonia slip**, fuel consumption and **practical/safety implications**
- **Catalyst deterioration** poorly known for zeolite, **real exhaust**, **and** **loco environment**
- References to **truck "successes"** are unproven in durability and degradation
- **Marine/Loco proposals are not consistent**

Technical Basis:

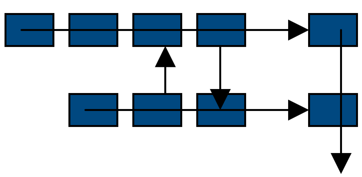
- Tier 2 engine-out NOx at 5.5g/hp-hr into SCR system
- Urea SCR only using a zeolite catalyst
- Locomotive exhaust temperature and duty cycle

Assessment Process

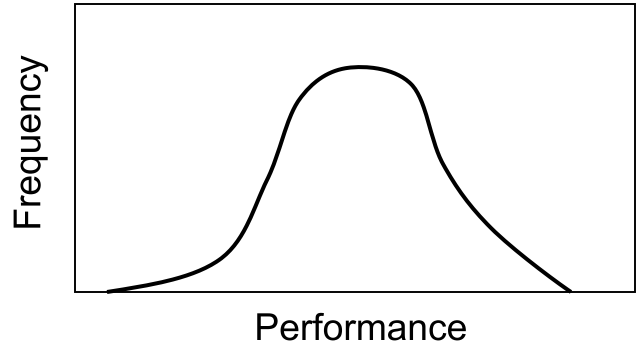
1. System Concept



2. Analytical Model

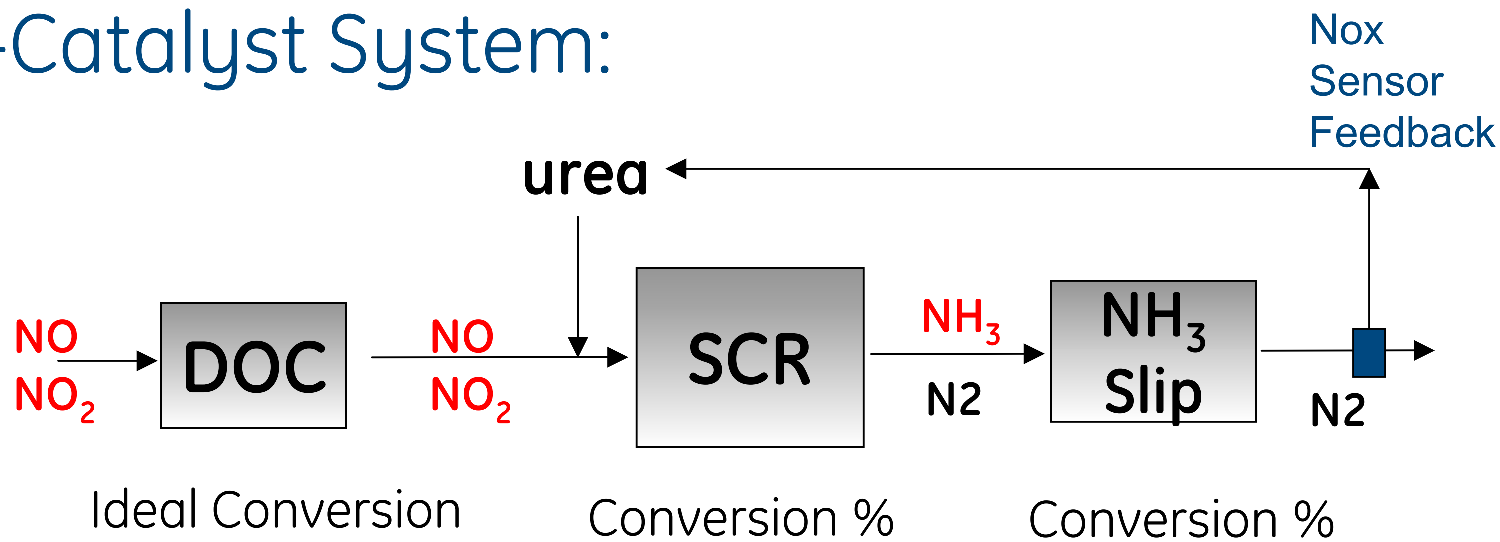


3. Monte Carlo Analysis



Urea-SCR: Nominal System Configuration

Three-Catalyst System:

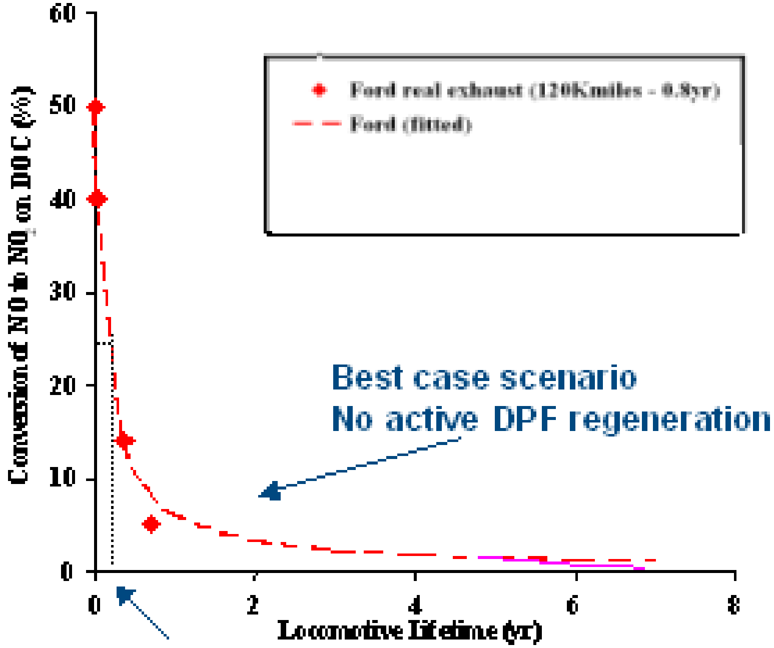


- DOC design provides optimum NO/NO_2 ratio when new
- Slip catalyst converts NH_3 to N_2 , with some NOx & NH_3

- **1.3g/bhp-hr requires 76% duty cycle NOx conversion at end of useful life**
- **Need ~85% peak conversion after degradation**

Deterioration - DOC

Deterioration under real exhaust

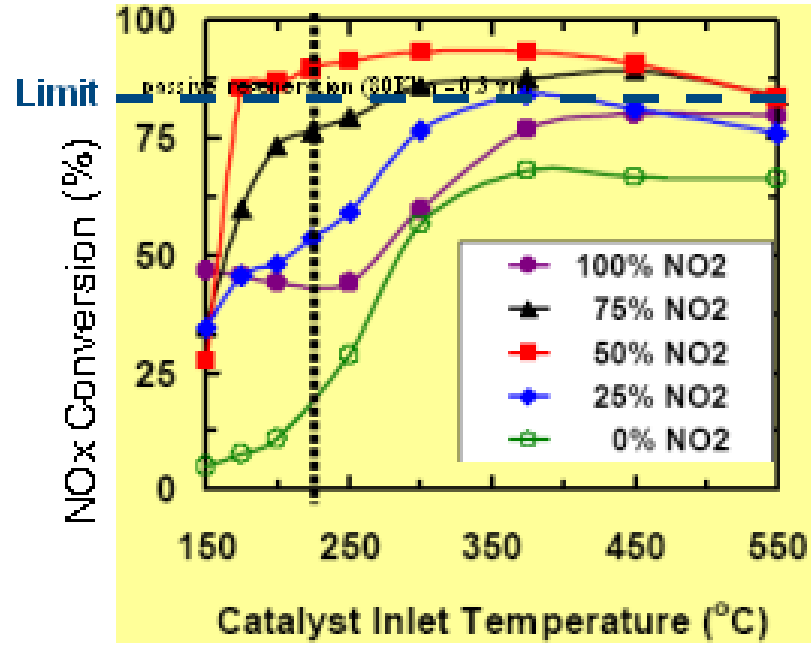


Replacement time

*Ref. C. Lambert, CLEERS, 2006, DEER 2006

SAE 2004-01-0072

Effect on SCR Performance:

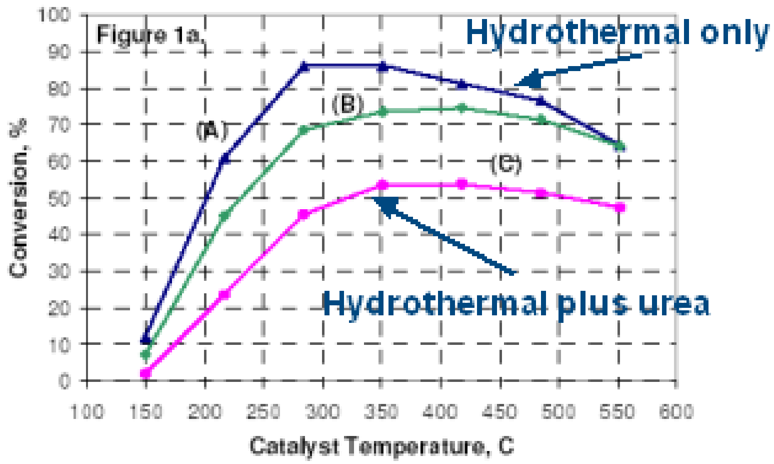


*Ref. J.H. Lee, General Motors, CLEERS, 2006

DOC will require replacement in <6 months

Deterioration - SCR

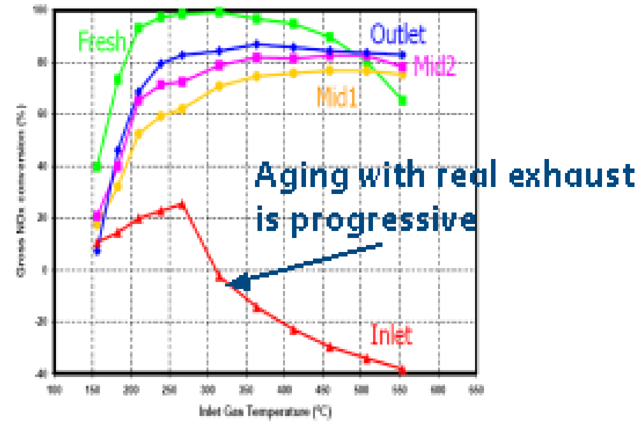
Hydrothermal vs. Chemical Deactivation



Ref. Ford & Pacific Northwest National Lab, North American Catalysis Society Meeting, Jun 2007, Session 4 Paper #50

Post Mortem of 120k mi SCR – Core#1

NO only and SV=30,000/hr



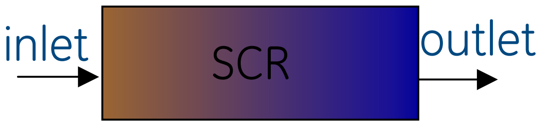
- 120k mi engine aging of SCR catalyst upstream of filter was non-uniform
- Outlet of engine aged SCR correlates well to the 64hr/670°C hydrothermal aging
- Inlet was most severely aged – work ongoing to understand

1:1 doping ratio

Ref. Ford, DEER 2006

"SCR catalysts that are engine aged with urea, deactivate in a more complicated manner than hydrothermal aging alone."

Ref. SAE 07PFL-397 in press 2007



Deterioration – Ammonia Slip Catalyst

Notch by notch dosing adjustment

Ref. BASF, SAE 2006-01-0640

- Deactivation of slip catalyst from 90%→ 80% ammonia conversion
- Assume selectivity to nitrogen remains at 80% (zero degradation)
- Inlet NOx for locomotive > trucks → higher ammonia slip levels
- Transient ammonia slip > 50 ppm possible due to large catalyst mass
- Potential to form N_2O due to NH_3 slip catalyst degradation
- Closed loop sensor needed – technology not available today

At 1.3 g/hp-hr, ammonia slip will be above the odor threshold

Comparison of Loco and Trucks

- Exhaust temperature in a locomotive is higher than in a truck
- Trucks use V-based catalyst, not applicable to locomotives in US . . . Locomotives require Zeolite catalyst – *not commercially available*
- 120,000 miles on a truck is approximate 8 months of locomotive operation
- Ammonia slip concerns for locos
  - Continuous ammonia slip due to high dosing
  - Transient ammonia slip > 50 ppm possible due to large catalyst mass

SCR Limitations

- Rate Limited (temperature)
- Mass Transfer Limited (catalyst size)
- NH_3 Limited (dosing accuracy & maldistribution)
- Thermal Aging / Poisoning (loss of sites)

Summary Assessment of Tier 4 NOx

- **New catalyst entitlement – consensus**
- **Larger impact of system interactions and variation**
  - *Deterioration of catalysts*
  - *ASC reconversion of NOx*
  - *Concern for ammonia slip*
  - *Full probabilistic analysis of variation*
- **High risk technology breakthroughs needed to get to <2.0 gm/HP-hr**

Advances required
NOx Sensor accuracy
NOx Sensor variation
DOC catalyst replace
SCR degradation
SCR variation
ASC Selectivity
ASC conversion
Zeolite catalyst

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General Aftertreatment Constraints

Sensitive to Exhaust Temperature:

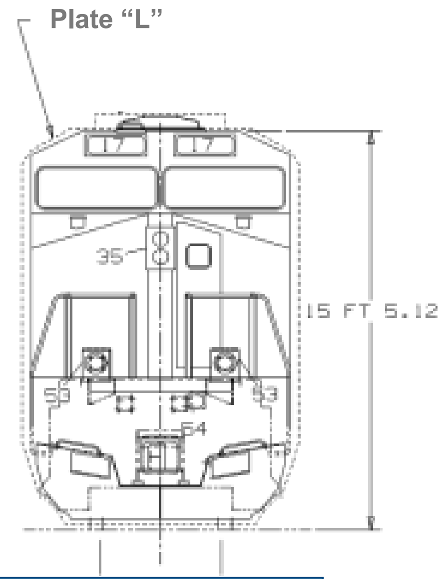
- Low temperature and low power/idle operation affects efficiency & soot loading
- High temperature, high altitude, tunnel operation affect durability

Packaging/Weight:

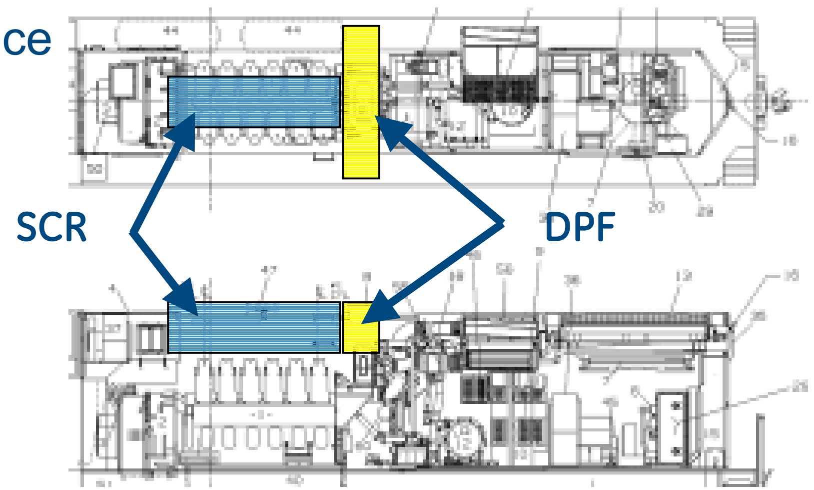
- Must mount above engine, limits device size and plumbing for reductant mixing
- High weight, will need significant structural support
- Impact to locomotive overall weight and balance

Mechanical Environment:

- Large housing, response to operating frequencies & thermal stress
- Shock loads due to hard couples, effect on substrate durability



Plus, reductant handling system and storage



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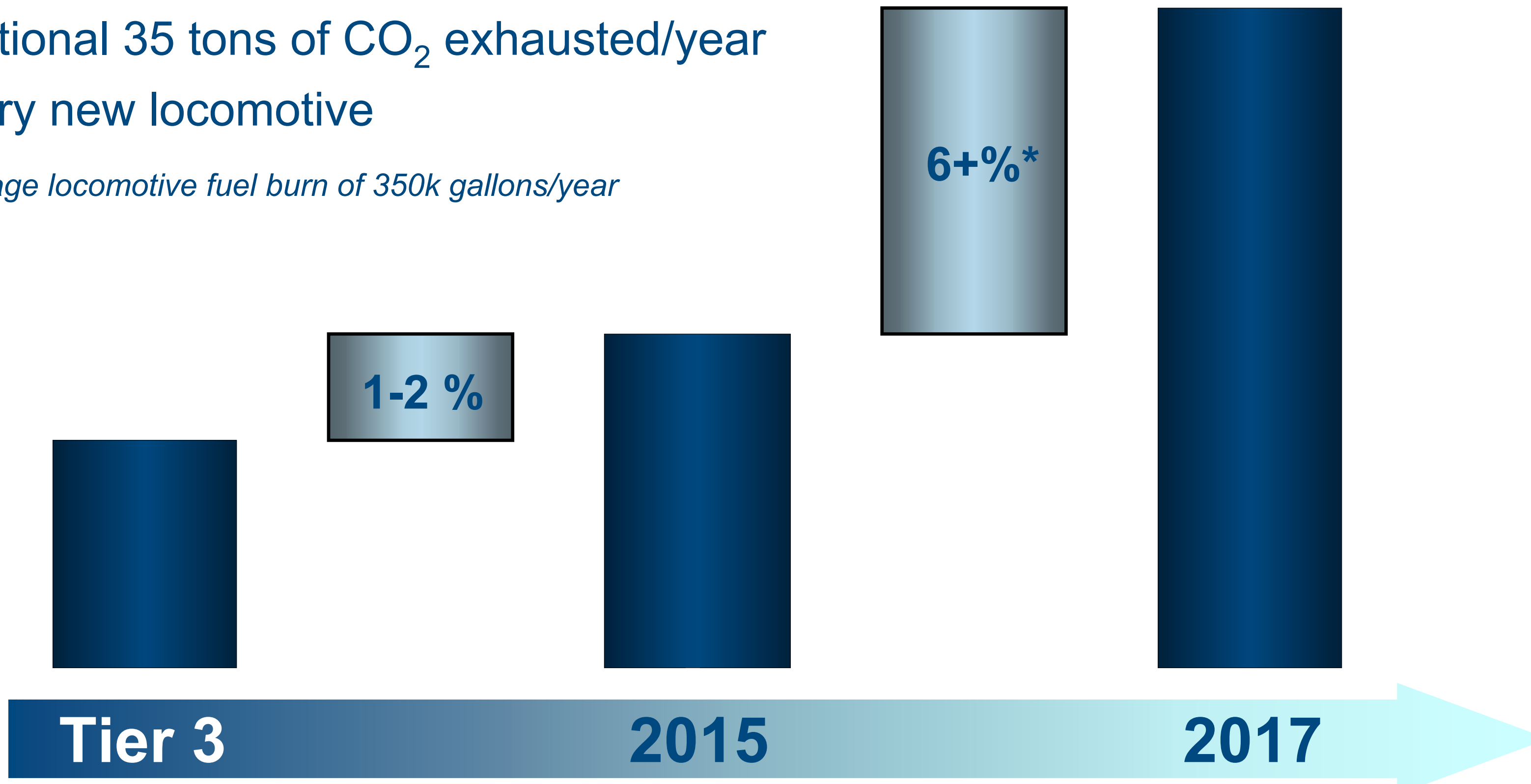
Fuel impact . . . new builds

Each point of fuel efficiency loss drives:

- An additional 3,500 gallons of fuel burned/year
- An additional 35 tons of CO_2 exhausted/year
- For every new locomotive

Assumes average locomotive fuel burn of 350k gallons/year



* Includes fuel loss from the reduction in catalyst efficiency

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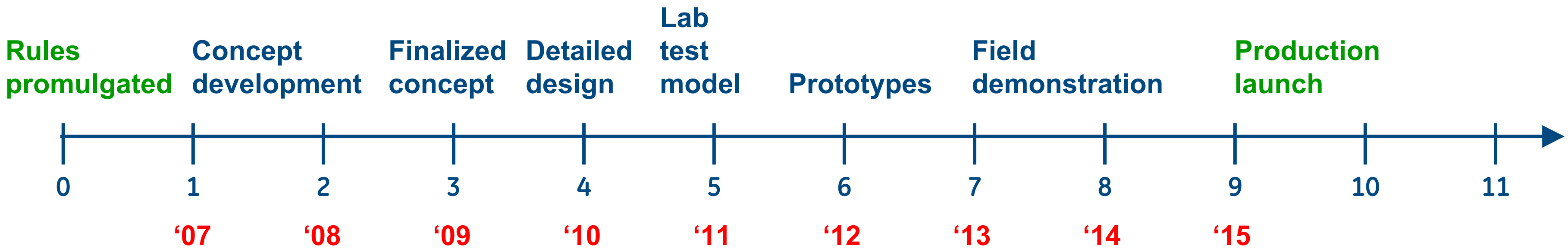
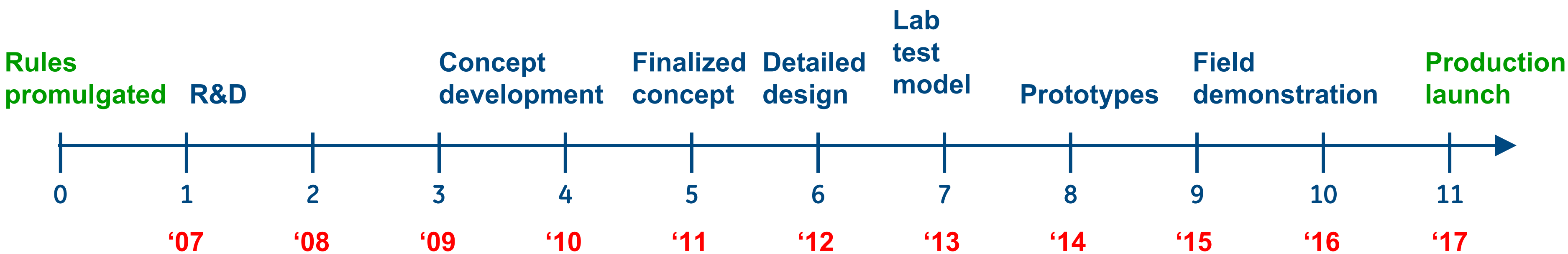
Tier 4 development timeline

Tier 4 PM



Tier 4 NOx



Based on successful Evolution launch . . .

Already feeling schedule pressure

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